COMPARISON OF ATMOSPHERIC STABILITY METHODS FOR CALCULATING AMMONIA AND METHANE EMISSION RATES WITH WINDTRAX

A. C. Koehn, A. B. Leytem, D. L. Bjorneberg

ABSTRACT. *Inverse dispersion models are useful tools for estimating emissions from animal feeding operations, waste storage ponds, and manure application fields. Atmospheric stability is an important input parameter to such models. The objective of this study was to compare emission rates calculated with a backward Lagrangian stochastic (bLS) inverse-dispersion model (WindTrax) using three different methods for calculating atmospheric stability: sonic anemometer, gradient Richardson number, and Pasquill-Gifford (P-G) stability class. Ammonia and methane emission data from a compost yard at a 10,000-cow dairy were used for the comparisons. Overall, average emission rates were not significantly different among the stability methods. Emission rates correlated well between the sonic and other methods ($r^2 > 0.79$, $p < 0.001$). The slopes of the regression lines between the sonic and Richardson methods were 0.95 and 1.0 for CH_4 and NH_3, respectively. The regression line slopes for the P-G method were about 1.9 for CH_4 and 1.6 for NH_3, which means emission rates predicted with the P-G method tended to be 50% to 100% greater than rates predicted with sonic anemometer data. Based on this limited data set, using the gradient Richardson method to represent atmospheric stability resulted in emission rates that more closely matched emission rates from the sonic method. Considering the amount of variability inherent in emissions calculations, a three-dimensional sonic anemometer should be used, if possible, to directly provide the necessary data to calculate parameters representing wind properties, rather than inferring values from other stability classification methods.*

Keywords. *Air emissions, Ammonia, Inversion dispersion model, Methane.*

There are concerns regarding the impact of the animal industry on air quality. One method for quantifying emissions is backward Lagrangian stochastic (bLS) inverse-dispersion modeling, such as the WindTrax model (Thunder Beach Scientific, Nanaimo, British Columbia, Canada). The WindTrax model has been used extensively to calculate ammonia (NH_3) and methane (CH_4) emissions from a variety of open sources, such as beef feedlots (Rhoades et al., 2010; Loh et al., 2008; Todd et al., 2008; Denmead et al., 2008; Flesch et al., 2007), dairies (McGinn et al., 2006; Leytem et al., 2011; Bjorneberg et al., 2009; Flesch et al., 2009), and grazing animals (Laubach and Kelliher, 2005; Laubach, 2010; McGinn et al., 2011). WindTrax has also been used to calculate CH_4 emissions from a biodigester (Flesch et al., 2011) and NH_3 emissions from manure applications to cropland and grassland (Sintermann et al., 2011). Studies with controlled releases of CH_4 showed that WindTrax-predicted emission rates were within 2% of known emission rates in an ideal situation without obstructions (Flesch et al., 2004) and within 10% when airflow was disturbed (Flesch et al., 2005a). Ro et al. (2013) showed that WindTrax-predicted emission rates were 88% of the known emissions from a lagoon with non-ideal surface conditions, demonstrating the accuracy and flexibility of the model for non-ideal situations.

The bLS method uses a mathematical model of the target gas dispersing from a source to a downwind location so that a downwind concentration measurement can establish the emission rate (Flesch et al. 2004, 2005b). In addition to a measured concentration, the WindTrax model requires the average wind speed and direction, surface roughness, and atmospheric stability to describe wind properties near the ground surface, as provided by Monin-Obukhov similarity theory, or MOST (Garratt, 1992). Atmospheric stability has an important influence on the wind, and stability is parameterized by Obukhov length (L). The value of L can be directly calculated using data from a 3-D sonic anemometer. If a sonic anemometer is not available, alternative measures of atmospheric stability are the Richardson number and Pasquill-Gifford (P-G) stability class. WindTrax will calculate the Richardson number from profiles of temperature and wind speed, and then directly calculate L. The P-G method was an early scheme for

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The authors are **Anita C. Koehn,** Soil Scientist, **April B. Leytem,** Research Soil Scientist, and **David L. Bjorneberg, ASABE Member Engineer,** Supervisory Research Agricultural Engineer, USDA-ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho. **Corresponding author:** David L. Bjorneberg, USDA-ARS Northwest Irrigation and Soils Research Laboratory, 3793 N 3600 E, Kimberly, ID 83341; phone: 208-423-6521; e-mail: dave.bjorneberg@ars.usda.gov.

classifying stability from very unstable (A) to neutral (D) to very stable (G) based on wind speed and cloud cover at night, and wind speed and incoming solar radiation during the day (Mohan and Siddiqui, 1998; USEPA, 2000). There is no formal relationship between P-G stability class and *L*, so WindTrax estimates *L* for each P-G stability class.

Published research studies using WindTrax typically measure wind statistics with three-dimensional sonic anemometers. Only three of the seventeen studies cited previously did not have data from a sonic anemometer. Two studies specified P-G stability class (Rhoades et al., 2010; Bjorneberg et al., 2009), and one study used temperature and wind speed profiles to calculate *L* (Todd et al., 2008). The objective of this study was to compare emission rates calculated with WindTrax using three different methods for determining atmospheric stability: sonic anemometer, gradient Richardson number, and P-G stability class. Since the bLS model was built upon MOST, which uses *L* to specify stability, this study essentially tested the effects of converting Richardson number and P-G stability class to *L* on predicted emission rates.

Materials and Methods

Weather data and trace gas concentrations were collected from a privately owned commercial dairy in southern Idaho with 10,000 milking cows. Detailed description of the data collection methods can be found in Leytem et al. (2011). For this study, CH_4 and NH_3 data were used from the compost yard, where a meteorological station and 3-D sonic anemometer were located. The compost yard was about 10 ha, with multiple compost windrows that were approximately 2 m high. The meteorological station recorded air temperature (type-T thermocouple) and wind speed (cup anemometer) at 2 and 4 m, and solar radiation, barometric pressure, and wind direction at 2 m. A three-dimensional sonic anemometer (R.M. Young, Traverse City, Mich.) was located on top of a 6 m tower at the south edge of the compost area and about 3 m from the meteorological station. All weather data were averaged over 15 min intervals.

Methane and ammonia concentrations were measured continuously with an Innova 1412 photoacoustic field gas monitor (1412 FGM, LumaSense Technologies, Santa Clara, Cal.) for 2 to 3 d each month from March 2008 until September 2008. No measurements were made in July 2008 when the monitoring equipment was being recalibrated. The detection limits of the gases were 0.1 mg L^{-1} for NH_3 and 0.4 mg L^{-1} for CH_4. Measurements were made near the center of the compost yard, approximately 2 m above the compost windrows. The measurement point was about 300 m north and west of the cattle pens and 1000 m west-northwest of the wastewater ponds. The prevailing wind was from the west, so emissions from the pens or wastewater pond should have had little impact on concentrations at the compost yard. Occasional east winds could have affected concentrations at the compost yard, which would affect absolute emission rates but would not affect comparisons of emission rates among different stability methods. The background gas measurements were made at a location 0.6 km south of the dairy (at 2 m height). The dairy was surrounded by range land on the north and irrigated crop land on the east, south, and west, with the nearest animal production facility 2.5 km southwest of the dairy.

Emission rates (kg ha^{-1} d^{-1}) were predicted with the WindTrax model using N = 50,000 trajectories, and the horizontal tracking distance was set at the minimum distance of 500 m for all scenarios. Atmospheric stability was determined with three different methods: P-G class, gradient Richardson number, and sonic anemometer data. Three-dimensional wind speeds and variances measured with the sonic anemometer were input into WindTrax to calculate wind speed, wind direction, surface roughness, and atmospheric stability, which is represented by the Monin-Obukhov length (*L*). Richardson number was calculated in WindTrax from the 2 and 4 m wind speed and temperature measurements.

The P-G method categorized stability into six classes, from very unstable (A) to very stable (F), according to the matrix used by Mohan and Siddiqui (1998). Daytime stability classes were determined by wind speed and solar radiation, with incoming solar radiation defined as slight when <300 W m^{-2} and strong when >600 W m^{-2} (table 1). Nighttime stability classes were determined from wind speed and cloud cover. Cloud cover estimates were obtained from National Weather Service data at Jerome, Idaho, about 17 km from the dairy. P-G stability classes were defined using wind speed from both 2 m (PG2) and 4 m (PG4) anemometers. P-G stability was also determined using the solar radiation/delta temperature (SRDT) method recommended by the EPA (USEPA, 2000). This method also uses wind speed and solar radiation for daytime stability, but uses wind speed and vertical air temperature gradient for nighttime stability (table 2). The temperature gradient was calculated from air temperatures measured at 2 and 4 m.

Simulations for each atmospheric stability method were run assuming that only the data for that method were available. Therefore, sonic anemometer data were not used to calculate surface roughness for the other methods. Surface roughness (z_0) was set at 0.15 m for both the P-G (PG2, PG4, and SRDT) and Richardson methods based on the general rule that z_0 is about one-tenth the height of the roughness element (Crenna, 2006), which was approximately 1.5 m for the compost windrows. This value falls between low crops with occasional obstacles (0.10 m)

Table 1. Matrix for determining Pasquill-Gifford stability class for PG2 and PG4 methods (adapted from Mohan and Siddiqui, 1998).

	Stability Class				
	Daytime: Solar Radiation ($W\ m^{-2}$)			Nighttime: Cloud Cover	
Wind Speed ($m\ s^{-1}$)	Strong (>600)	Moderate (300-600)	Slight (<300)	Cloudy or Overcast	Clear or Partly Cloudy
<2	A	B	B	E	F
2-3	B	B	C	E	F
3-5	B	C	C	D	E
5-6	C	C	D	D	D
>6	C	D	D	D	D

Table 2. Matrix for determining Pasquill-Gifford stability class using solar radiation/delta-T method (USEPA, 2000).

Daytime Stability Class:

Wind Speed ($m\ s^{-1}$)	Solar Radiation ($W\ m^{-2}$)			
	≥925	925-675	675-175	<175
<2	A	A	B	D
2-3	A	B	C	D
3-5	B	B	C	D
5-6	C	C	D	D
>6	C	D	D	D

Nighttime Stability Class:

Wind Speed ($m\ s^{-1}$)	Vertical Temperature Gradient	
	<0	≥0
<2	E	F
2.0-2.5	D	E
≥2.5	D	D

and high crops with scattered obstacles (0.25 m) in EPA guidance (USEPA, 2000) and is also the maximum value that a user can input in the WindTrax interface. Users could input surface roughness values >0.15 m through an input data file if they determined that a larger value was justified. Surface roughness was calculated in WindTrax for the sonic method using the wind statistics from the sonic anemometer. These calculated values of z_0 may exceed 0.15 m. Friction velocity (u*) was calculated in the model from sonic anemometer data (sonic), wind speed and temperature profile data (Richardson method), or inferred from empirical functions relating u* to wind speed, stability, and surface roughness for the P-G methods (Crenna, 2006). Emission rate estimates for each method were filtered according to the criteria of Flesch et al. (2005b), where emission rates having values of $u^* \leq 0.15$ (low wind conditions), $|L| \leq 10$ m (strongly stable/unstable atmosphere), and $z_0 \geq 1.0$ m (associated with errors in the wind profile) were removed from the comparisons. The P-G methods were only filtered based on u* because WindTrax does not output L for P-G stabilities. The Richardson method was filtered for u* and L, while the sonic method was filtered for all three parameters. In some cases, the background concentration was greater than the concentration at the compost yard, resulting in a negative emission rate. These negative emission rates were also removed from analysis.

Ammonia and methane emission rates determined from the five stability methods were compared using only data from measurement intervals when values were available for all five methods to eliminate any bias caused by using data from different periods of the day. Ammonia and methane emission rates tend follow diurnal trends (Rhoades et al., 2010; Leytem et al., 2011), so results will be biased if values are not available at the same time of day for all methods. The data were not normally distributed, so the five methods were statistically compared by a nonparametric method using Proc GLM (SAS, 2008) to analyze the ranked results for each month. Tukey's test was used to assess multiple comparisons between the ranked median with $p < 0.10$. Data were also evaluated for the average of all six months by log transforming the emission estimates and using Proc Mixed with repeated measures (month) to determine the main effects of method. Differences in methods were evaluated using least squared means with Tukey's adjustment ($p < 0.10$).

RESULTS AND DISCUSSION

The basis of inverse dispersion modeling with WindTrax is that there is a relationship between an unknown emission rate from a source and the concentration increase measured in the emission plume. This relationship is determined with a dispersion model that describes the mixing of gases as they are transported downwind (Flesch et al., 2009). The relative differences among stability methods should be similar for both CH_4 and NH_3 because WindTrax only considers the dispersion of gases. Emission rates were calculated for both gasses to provide more data for comparisons in situations where concentration data may be missing.

The filtering criteria resulted in different numbers of observations for each stability method. The number of observations remaining in a month after filtering ranged from 40% to 90% of the total observations for the three P-G methods, from 30% to 60% for the Richardson method, and from 10% to 70% for the sonic anemometer method. The P-G stability class methods were only filtered for u* because the method does not output L, whereas the Richardson and sonic methods calculate L, adding an additional filtering criterion. Data from the sonic anemometer method were filtered further based on z_0, while this parameter was set at a constant 0.15 m for the other methods. Using only data from time intervals when values were available for all five methods further reduced the number of observations for monthly comparisons (table 3).

Median CH_4 emission rates were not significantly different among methods for any month in this study (table 3). For NH_3, the median emission rate for the sonic

Table 3. Median monthly emission rates for methane and ammonia using only observations (Obs.) when data were available for all five methods (emission values are in $kg\ ha^{-1}\ d^{-1}$).

Month	No. of Obs.	Method				
		PG2	SRDT	PG4	Richardson	Sonic
Methane						
Mar.	19	156	150	171	159	117
Apr.	52	153	196	147	156	155
May	50	106	94	109	109	92
June	12	912	813	947	619	439
Aug.	53	91	91	106	99	68
Sept.	14	35	34	36	41	25
Total	200					
Avg.[a]		194	188	201	153	134
RMSD		179	152	179	72	-
Ammonia						
Mar.	36	14	14	15	14	10
Apr.[b]	52	23 a	24 a	22 ab	21 ab	18 b
May	54	6	5	6	6	4
June	13	43	42	45	40	30
Aug.[b]	78	27 ab	28 ab	30 a	28 ab	24 b
Sept.	27	11	11	11	12	8
Total	260					
Avg.[a]		24	23	25	21	18
RMSD		14	13	15	7	-

[a] Avg. = average of all emission rates; RMSD = root mean square of deviation of emission rates from the sonic method.

[b] Within the row, values followed by different letters are significantly different. Values without letters are not significantly different.

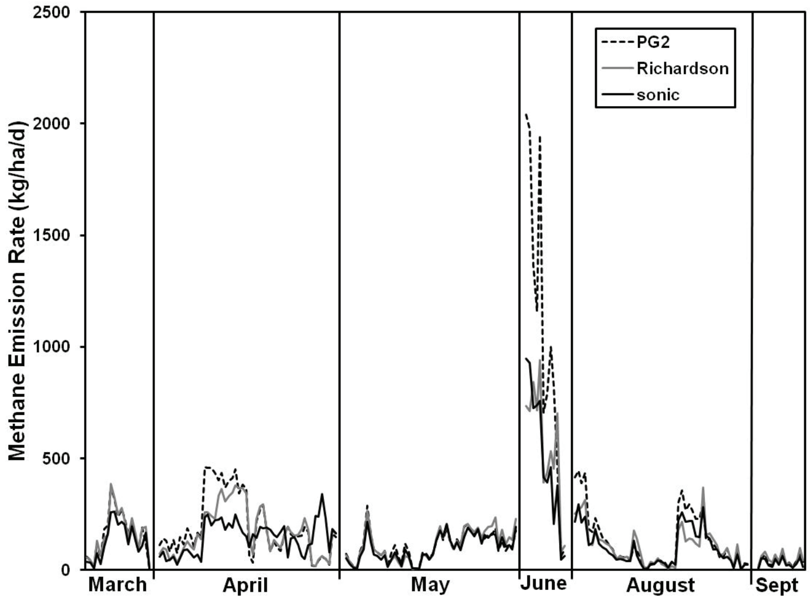

Figure 1. Predicted methane emission rates with atmospheric stability determined by PG2, Richardson, and sonic methods.

method was less than that for the PG2 and SRDT methods in April and less than PG4 in August. Although CH_4 emission rates were not significantly different for any month, the numeric differences among median emission rates were often quite large. For example, the predicted CH_4 emission rate in June using the sonic method was 52% less than the PG2 method and 46% less than the SRDT method. Predicted emission rates in June were also much greater than any other month.

Figures 1 and 2 show the predicted CH_4 and NH_3 emission rates, respectively, for the PG2, Richardson, and sonic methods. The relative differences among the methods were similar for CH_4 and NH_3 because the wind statistics data were the same for both parameters. Methane emission rates were similar among the three methods except for (1) a period in April when the PG2 and Richardson methods were greater than the sonic method, (2) another period in April when the PG2 and Richardson methods were lower than the sonic method, and (3) in June when the PG2 method was greater than the other two methods (fig. 1). The differences in CH_4 emission rates between the PG2 and sonic methods exceeded 1000 kg ha^{-1} d^{-1} for three of the 12 values in June, and six of the 12 values were at least double the values for the sonic method. The two periods when emissions were greater than the sonic method occurred in the afternoon and early evening, and the one period when emissions were less than the sonic method occurred in the early morning. There were no obvious reasons for the differences among the three methods, such as high wind speeds or very stable conditions. There also was no

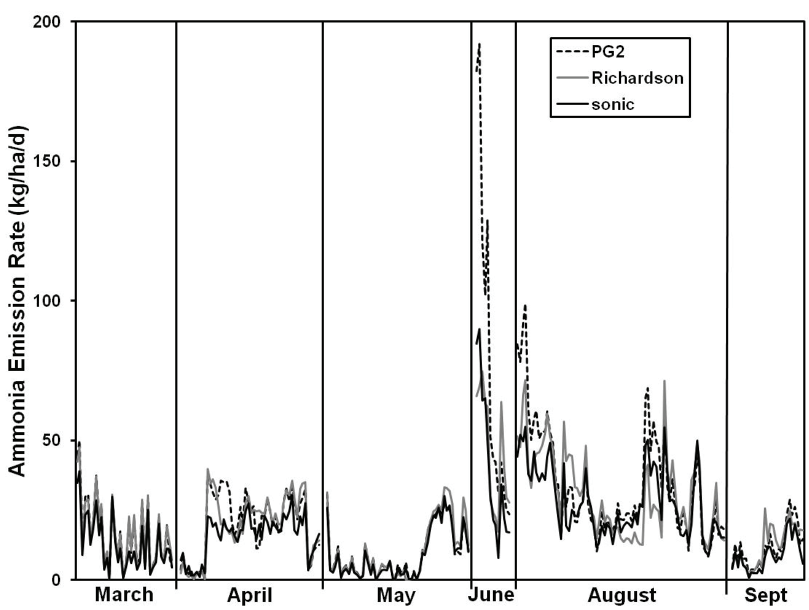

Figure 2. Predicted ammonia emission rates with atmospheric stability determined by PG2, Richardson, and sonic methods.

Table 4. Correlations between emission rates predicted by the sonic method and other methods.

	Ammonia		Methane	
Sonic vs.	r^2	Slope	r^2	Slope
PG2	0.85	1.56	0.86	1.91
SRDT	0.86	1.51	0.92	1.85
PG4	0.87	1.67	0.86	1.91
Richardson	0.83	1.00	0.79	0.95

correlation between differences in emission rates and differences in L between the Richardson and sonic methods.

When evaluated over the six-month period, there were no significant differences among overall average emission rates for either CH_4 or NH_3 emissions (table 3). However, the numeric differences in overall average emission rates with the P-G methods were 40% to 49% greater for CH_4 and 29% to 38% greater for NH_3 than with the sonic method. Emission rates with the Richardson method were 14% and 17% greater for CH_4 and NH_3, respectively, than with the sonic method. Todd et al. (2008) reported only a 4% difference between emission rates calculated by the WindTrax model using wind speed and air temperature profiles (Todd et al., 2008) or sonic anemometer data (Flesch et al., 2007). Those two studies, however, only had seven days of common data.

Since a 3-D sonic anemometer provides the necessary data for all wind statistics needed for dispersion modeling in WindTrax, emission rates calculated with the sonic method were assumed to be the most representative. Therefore, we correlated all values from the other four methods with the sonic method. The coefficients of determination were greater than 0.79 ($p < 0.001$) for all methods (table 4). The slopes of the regression lines for the Richardson method were 0.95 and 1.0 for CH_4 and NH_3, respectively, indicating that the predicted emission rates for these two methods were similar. The root mean square of the deviation from the sonic method was 72 kg^{-1} ha^{-1} d^{-1} for CH_4 and 7 kg^{-1} ha^{-1} d^{-1} for NH_3, which was about one-half or one-third of the overall average values (table 3). The regression line slopes for the P-G methods were about 1.9 for CH_4 and 1.6 for NH_3, indicating that emission rates predicted with the P-G methods tended to be 50% to 100% greater than the rates predicted with sonic anemometer data. Root mean squares of the deviations from the sonic method were also greater for the P-G methods than the Richardson method (table 3). The Richardson number and L are uniquely related measures of stability, while there is no direct relationship between P-G stability class and L, so it is understandable that the sonic and Richardson methods matched more closely than the sonic and P-G methods. Reducing the surface roughness would reduce the predicted emission rates, provided that all other variables were constant. If predicted emission rates were consistently greater with the PG and Richardson methods than with the sonic method, this would indicate that the surface roughness was too high. However, this was not the case, as shown in figures 1 and 2.

Emission rates were not significantly different between the PG2 and SRDT methods for CH_4 or NH_3 for any month (table 3). Median monthly CH_4 emission rates varied <12% between the two methods, except in April when PG2 was 22% less than SRDT (table 3). Median monthly NH_3 emission rates varied <10% between the SRDT and PG2 methods. The slight differences in criteria defining stability classes resulted in similar predicted emission rates even though the SRDT method had fewer values in stability classes B (unstable) and E (stable) and more values in stability class D (neutral) than the PG2 method (table 5).

Table 5. Relative number of observations in each atmospheric stability class for the PG2 and SRDT methods for all six months of the study, based on a total of 260 observations for time periods when data were available for all methods.

Stability	Relative Number of Observations (%)	
Class	PG2 Method	SRDT Method
A	0	0
B	26	10
C	26	23
D	21	48
E	27	18
F	1	0

CONCLUSIONS

Few significant differences occurred among median monthly predicted emission rates for the five methods. When comparing common data, however, emission factors could be twice as large when atmospheric stability was input from a P-G method compared to direct calculations in WindTrax from sonic anemometer data, especially for time periods with limited data. Although overall average emission rates for the six-month period were not statistically different, emission factors derived from the P-G methods were 40% to 50% greater than the sonic method for CH_4 and 20% to 40% greater for NH_3. The average emission rates for the gradient Richard method were 14% and 17% greater than the sonic method for CH_4 and NH_3, respectively. Based on this limited data set, inputting wind and temperature profiles into the WindTrax model resulted in emission rates that more closely matched emission rates from the sonic method than did the P-G methods. Since the Richardson number is uniquely related to L, it is understandable that the sonic and Richardson methods closely matched. Considering the amount of variability inherent in emissions calculations, a three-dimensional sonic anemometer should be used, if possible, to directly provide the necessary data to calculate parameters representing wind properties, rather than inferring values from other stability classification methods, when using dispersion models.

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